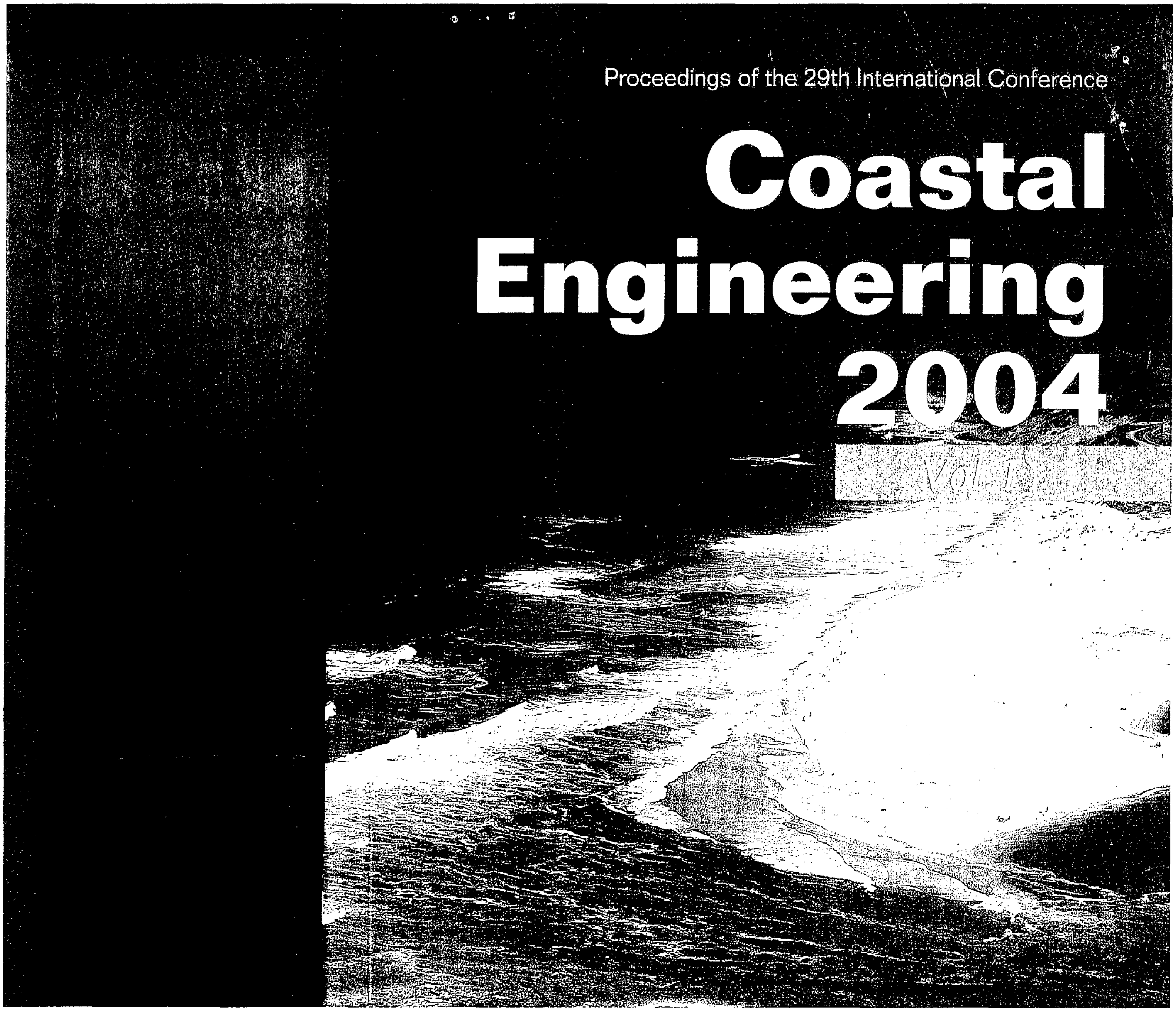

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DISSIPATION OF NONLINEAR SHALLOW WATER WAVES

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Nonlinear frequency domain formulations of extended Boussinesq equations are studied. The new formulation retains the natural split between continuity and momentum equations, allowing for the dissipation term to be incorporated directly into the momentum equation. Additionally, due to the strong resemblance to the time domain equation, an inverse FFT technique can be used to calculate the nonlinear terms in the time domain, enacting a substantial computational savings. Lastly, a recently-published parameterization for the evolutionary behavior of the high wavenumber tail of surf zone spectra was tested against laboratory data. The experimental parameters of these data may be near the limits of validity for the parameterization, yet the formulation works surprisingly well. These encouraging results may lead the way toward incorporating the parameterization into a nonlinear wave transformation model.

1. Introduction and Wave Models

In the nearshore and surf zones, waves undergo substantial transformation in the last three to five surfzone widths from the beach. Wave nonlinearity, which serves to transfer energy from low frequencies to high, becomes amplified in the nearshore; this is usually evident in the spectrum by the amplification of frequency harmonics of the spectral peak. The energy buildup in the high frequencies is then preferentially destroyed by dissipation and breaking.

There are a plethora of models which simulate this behavior. These are cast into either the time domain or the frequency domain, and are formulated in many different forms, including various extensions of the Boussinesq equations and nonlinear augmentations of the fully dispersive

mild-slope equations. The one generally-subscribed, first order weakness in these models is the description of wave breaking.

The recently-completed Nearshore Community Model (NearCoM; Kirby 1999)[1] provided a context for the inclusion of a frequency domain phase resolving nonlinear wave model into the modeling system, as it was based on the coupling of individual wave, circulation and sediment transport modules. Each of these modules also requires some computational expediency, which is an issue with the frequency domain models for large numbers of frequency components. Unfortunately, Kaihatu and Kirby (1996)[2] determined that skewness and asymmetry statistics are quite sensitive to the number of frequency components retained in the simulation; thus there is some need to increase the computational speed of these models.

Bredmose et al. (2001)[3], Bredmose et al. (2002)[4] and Bredmose (2002)[5] detail the use of inverse FFT techniques for representing the nonlinearity in frequency domain models. Instead of representing the nonlinearity in these equations in terms of triadic interactions across all frequencies and then summed over the spectrum (requiring $O(N^2)$ operations, where N is the total number of frequencies), they assembled the nonlinear term in the time domain by inverse FFT and then switching back and forth between time and frequency domains, which requires only $O(N \log N)$ operations. For 500 frequency components, this is a difference between 250,000 operations and just over 1,300 operations, a significant savings. In order to use this technique, a strong correlation between the time domain and frequency domain needs to exist. This precludes those models based on nonlinear extensions of the mild-slope equation, since they have coefficients which are functions of wave-related quantities, implying at least a split between temporally periodic and slow temporal variations. (We note here that Bredmose et al. (2002)[4] inferred the time domain nonlinearity from the nonlinear frequency domain summations for their version of the fully dispersive shoaling model for the case of exact resonance). Thus, we turn to the extended Boussinesq equations, which have a clear time domain form within which the nonlinear terms may be calculated.

Frequency domain versions of the model of Madsen et al. (1991)[6] have been developed (e.g. Eldeberky and Battjes 1996[7]; Kofoed-Hansen and Rasmussen 1998[8]). Kaihatu and Kirby (1998)[9] developed a frequency domain version of the model of Nwogu (1993)[10]. This model is substantially more complicated that other models of its type, and transformation into the frequency domain is not straightforward. Adopting a variation of the procedure of Liu et al. (1985)[11], Kaihatu and Kirby (1998)[9] reduced the continuity and momentum equations to a single equation, then used a free shoaling parameter to improve the shoaling behavior beyond that which would result naturally from the manipulation (which turned out to be quite unsatisfactory). It was later determined (Kaihatu 2003[12]) that the resulting frequency domain model of Kaihatu and Kirby (1998)[9] performed poorly in predicting third moments and possessed poor directional behavior.

2. Wave Dissipation in Nonlinear Frequency Domain Models

Unlike wave breaking in time domain nonlinear models, where dissipation can be triggered by steepness exceedance criteria which are evaluated locally, wave breaking in frequency domain models is usually incorporated via the combination of a narrow banded dissipation function (e.g. Battjes and Janssen 1978[13]; Thornton and Guza 1983[14]) and an assumption of the frequency distribution of that dissipation. Mase and Kirby (1992)[15] and Kirby and Kaihatu (1996)[16] postulated that the proper distribution of wave dissipation across frequencies was achieved by weighting this dissipation with the square of the frequency; the latter also provided physical arguments for this distribution. Chen et al. (1997)[18] used field and laboratory data, in conjunction with a frequency domain Boussinesq model, to determine that third moments such as skewness and asymmetry can be best simulated using the frequency squared distribution.

While promising, the wave dissipation as formulated in frequency domain models is problematic in that it is unable to capture any local effects of wave breaking. The dissipation remains an active energy drain weighted by (for example) the ratio of waveheight to water depth, and is thus small offshore and high near the surf zone. However, any of the sharp dissipative effects seen in a single realization of a breaking wave are smeared over the spectral range; this is hypothesized to be responsible for poor skewness and asymmetry comparisons in very shallow water (Kaihatu 2003)[12]. Kirby and Kaihatu (1996)[16] and Bredmose et al. (2002)[4] investigated the efficacy of incorporating a local breaking wave description into the frequency domain models; the latter made use of inverse FFT to cast the breaking wave into the time domain. One particularly promising approach is the model of Veeramony and Svendsen (2000)[17], in which the vorticity dynamics inherent in the breaking process were added to the breaking formulation. The incorporation of this effect in the frequency domain models would likely give the localized breaking effect desired.

3. Two-Equation Model

The likely cause for the poor behavior exhibited by the model of Kaihatu and Kirby (1998)[9] is the ambiguity in the procedure used to reduce the equations of Nwogu (1993)[10] to one for the free surface η. The extended Boussinesq equations of Nwogu (1993)[10] are:

$$\eta_t + \nabla \cdot [(h+\eta)\,\mathbf{u}] + \nabla \cdot \left\{ \left(\frac{z_\alpha^2}{2} - \frac{h^2}{6} \right) h \nabla(\nabla \cdot \mathbf{u}) + \left(z_\alpha + \frac{h}{2} \right) h \nabla \left[\nabla \cdot (h\mathbf{u}) \right] \right\} = 0 \quad (1)$$

$$\mathbf{u}_t + g\nabla\eta + (\mathbf{u}\cdot\nabla)\mathbf{u} + z_\alpha \left\{ \frac{z_\alpha}{2} \nabla(\nabla\cdot\mathbf{u}_t) + \nabla[\nabla\cdot(h\mathbf{u}_t)] \right\} = 0 \quad (2)$$

where η is the free surface elevation and the horizontal velocity vector $\mathbf{u}$ is located at a point z_α in the water column. This elevation becomes a free parameter used to optimize the equations' dispersion relation:

$$C^2 = \frac{\omega^2}{k^2} = gh \left[\frac{1 - \left(\alpha + \frac{1}{3}\right)(kh)^2}{1 - \alpha(kh)^2} \right] \quad (3)$$

where:

$$\alpha = \frac{z_\alpha^2}{2h^2} + \frac{z_\alpha}{h} \quad (4)$$

Nwogu (1993)[10] determined that the best fit to full linear dispersion is achieved with $\alpha = -0.390$.

Kaihatu and Kirby (1998)[9] used first order substitutions between η and $\mathbf{u}$ to reduce the two equations into one for the free surface only (at least in the linear terms). In order to preserve the original equations' dispersive characteristics, however, the time derivatives of one of the first order substitutions needed to be made. While this retained optimal dispersion characteristics, it destroyed the ability of the resulting model to perform reasonable shoaling calculations. Kaihatu and Kirby (1998)[9] circumvented this difficulty by adding a second order wave equation to the combined equation, multiplied by a coefficient which could be tuned to match shoaling from linear theory.

While initially promising, the resulting equation performed poorly in skewness and asymmetry predictions and possessed subpar directional characteristics. Theoretically, more optimization could be performed; however, it is likely that more problems would be created as others were solved.

Alternatively, we can address the problem by retaining the split between continuity and momentum equations and assuming:

$$\eta = \sum_{n=1}^{n=N} \frac{A_n}{2} e^{i(\int k_n dx - n\omega t)} + c.c. \quad (5)$$

$$u = \sum_{n=1}^{n=N} \frac{B_n}{2} e^{i(\int k_n dx - n\omega t)} + c.c. \quad (6)$$

$$v = \sum_{n=1}^{n=N} \frac{D_n}{2} e^{i(\int k_n dx - n\omega t)} + c.c. \quad (7)$$

This will triple the number of equations to solve but will maintain a close relationship between the time domain and frequency domain versions of the model.

3.1. *One Dimension*

We first derive a shoaling model based on a one-dimensional reduction of (1) and (2). Substituting (5) and (6) into (1) and (2) and making the assumption of near-resonant interactions between triadic components yields:

$$\begin{aligned} &-i\omega_n A_n \\ &+ \left\{ (1 - Qk_n^2h^2)h_x - 3k_n\left(\alpha + \frac{1}{3}\right)h^3k_{nx} - ik_n^3h^3\left(\alpha + \frac{1}{3}\right) \right\} B_n \\ &+ \left\{ \left(1 - 3k_n^2h^2\left(\alpha + \frac{1}{3}\right)\right)h + 2iQk_nh^2h_x + 3i\left(\alpha + \frac{1}{3}\right)h^3k_{nx} \right\} B_{nx} \\ &= -\frac{i}{4}\left\{ \sum_{l=1}^{n-1} S\left(A_lB_{n-l} + B_lAn - l\right)e^{i\Theta} + 2\sum_{l=1}^{N-n} T\left(A_l^*B_{n+l}B_l^*A_{n+l}\right)e^{i\Upsilon} \right\} \end{aligned} \quad (8)$$

$$\begin{aligned} &gA_{nx} + igk_nA_n + \left\{ i\omega_n\left[\alpha k_n^2h^2 - 1\right] + \omega_n\alpha h^2k_{nx} + \omega_nRhh_xk_n \right\} B_n \\ &+ \left[2\omega_n\alpha h^2k_n - i\omega_nRhh_x \right] B_{nx} \\ &= -\frac{i}{4}\left\{ \sum_{l=1}^{n-1} SB_lB_{n-l}e^{i\Theta} + 2\sum_{l=1}^{N-n} TB_l^*B_{n+l}e^{i\Upsilon} \right\} \end{aligned} \quad (9)$$

where:

$$Q = 3\alpha + 2\sqrt{1+2\alpha} \quad (10)$$

$$R = 2\sqrt{1 + 2\alpha} - 2 \tag{11}$$

$$S = k_l + k_{n-l} \tag{12}$$

$$T = k_{n+l} - k_l \tag{13}$$

$$\Theta = \int (k_l + k_{n-l} - k_n)\, dx \tag{14}$$

$$\Upsilon = \int (k_{n+l} - k_l - k_n)\, dx \tag{15}$$

These equations can be modeled using a fourth-order Runge Kutta solver. In an unknown coincidence, Bredmose (2002)[5] also derived (8) and (9), using the method of Scraton (1964)[19] for solution.

3.2. *Parabolic Two-Dimensional Model*

We also investigated the development of a parabolic two-dimensional model from the Boussinesq equations (1) and (2). One potential issue is the ordering of the longshore particle velocity v and its associated complex amplitude D_n. The assumption made here is that the standard truncations used for the parabolic approximations are sufficient for ordering the longshore particle velocities. Not surprisingly, the resulting equations are quite complicated. At the time of this writing, their derivation has not been fully checked, so we do not present them here.

4. Parameterization

In wind wave generation, parameterization of the behavior of the high frequency tail is standard modeling protocol (Hasselmann and Hasselmann 1985)[20] due to the magnitude of the computational effort required to calculate the quartet interactions across the directional spectrum. However, similar parameterization efforts for nearshore spectra have not kept apace; prior to 2003, only Thornton (1977)[21] and Zakharov (1999)[22] have proposed parameterized equilibrium spectral shapes for nearshore and surf zone wave spectra.

Recently, Smith and Vincent (2003)[23] proposed equilibrium shapes for surf zone spectra based on the earlier work of Zakharov (1999)[22] and Toba (1973)[24]. They noted that the high wavenumber range of surf zone spectra had two characteristic slopes: $k^{-4/3}$, seen from $k = 2.5k_p$ (where k_p is

the wavenumber of the spectral peak) to $kh = 1$, consistent with Zakharov (1999)[22], and $k^{-5/2}$, in the range $kh > 1$, consistent with Toba (1973)[24]. Based on an analysis of various laboratory and field data sets, they determined a parameterized form for the wavenumber spectrum energy density for the wavenumber range $k > 2.5k_p$.

We tested the parameterization of Smith and Vincent (2003)[23] using laboratory data sets and nonlinear wave model runs which do not make up part of the original data set used to develop the parameterization. One data set used in this test was that of Mase and Kirby (1992)[15], which was primarily used as a test of the dispersive properties of nearshore nonlinear wave models. Random waves with a peak frequency $f_p = 1Hz$ were allowed to shoal up a sloping beach; the water depth at the toe of the slope $h_o = 0.47m$, leading to $kh = 1$ at the peak frequency, a severe test of nonlinear wave models. Figure 1 shows an example of the comparison between the parameterization of Smith and Vincent (2003)[23], the data of Mase and Kirby (1992)[15] for $h = 0.10m$, and the nonlinear shoaling model of Kaihatu and Kirby (1995)[25] with the nonlinear correction of Kaihatu (2001)[26]. While the parameterization is not capable of capturing the amplification of the second harmonic of the spectral peak evident in the data, it is capable of predicting the general energy level in the high frequency tail of the wave spectra in the experiment. The fact that it matches the data of Mase and Kirby (1992)[15] as well as it does is remarkable in light of the fact that much of the high frequency range is in deep water up until $h = 0.125m$.

According to Herbers et al. (2000)[27], the high frequency range of surf zone spectra tend towards a flat, featureless shape in the inner surf zone. Smith and Vincent (2003)[23] demonstrate that their parameterization is capable of replicating the evolution toward this shape through the surf zone. In consideration of the computational effort required for simulating nearshore nonlinear wave transformation, the ability to represent the evolution of part of the spectrum with a parameterization would be welcome. It is important to note that this does not obviate the need for nonlinear wave models since the parameterization is incapable of producing important quantities for sediment transport (e.g. skewness, asymmetry). However, the parameterization can be used as an additional means of validating the equilibrium behavior of nonlinear models, much in the same way that wind wave generation models are compared to fetch-limited growth formulations.

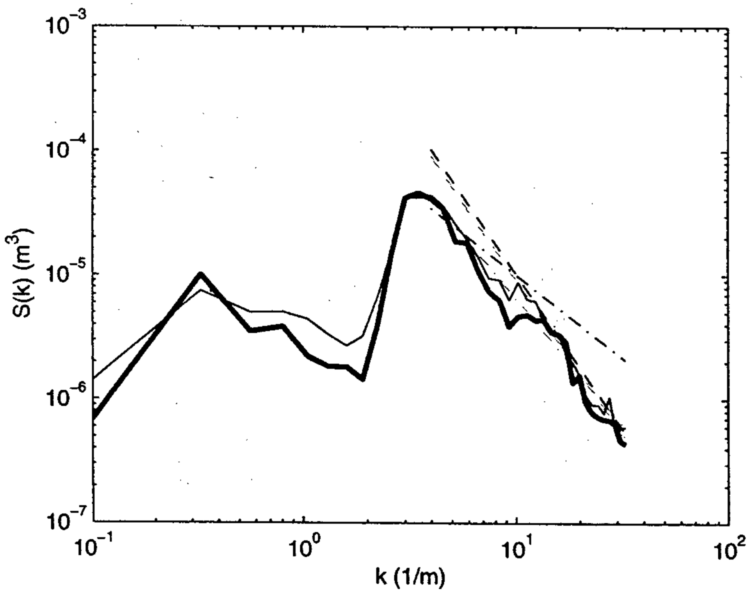

Figure 1. Comparison of wavenumber spectra from experiment to nonlinear model and parameterization, $h = 0.1m$. Thick line: Data of Mase and Kirby (1992). Thin line: Model of Kaihatu and Kirby (1995) and Kaihatu (2001). Dash-dot line: Parameterization of Smith and Vincent (2003), Zakharov range. Dashed line: Parameterization of Smith and Vincent (2003), Toba range.

5. Discussion

In this paper we discussed a few difficulties encountered with the frequency domain extended Boussinesq model of Kaihatu and Kirby (1998)[9]. It is felt that these problems stem from the rather complicated nature of the transformation of the original equations of Nwogu (1993)[10] into the frequency domain. To circumvent that, we retained the original forms of the equations, then derived the frequency domain model based on transformations of the free surface and both components of velocity. The resulting equations retain more fidelity to the original time domain model of Nwogu (1993)[10], thus allowing the incorporation of the inverse FFT technique of Bredmose et al. (2001)[3] for calculating the nonlinear terms. Additionally, frequency domain formulations of models of local wave breaking would be easier to implement since there is now a set of momentum equations where the dissipation can be included.

In the interest of further computational efficiency, a useful and accurate

parameterization of the high frequency behavior of the evolving wave spectra could be incorporated in a nonlinear nearshore wave model, analogous to the parameterized range of deep water wave spectra evolution in wind wave models. We tested the accuracy of the surf zone parameterization of Smith and Vincent (2003)[23] using data from experiments which parameters may be at the fringes of the validity of the parameterization. The case of the experiment of Mase and Kirby (1992)[15] is discussed, and it was deteremined that the parameterization generally worked well, all the more encouraging since the relative depth of the experimental condition is quite large relative to those of the experiments making up the parameterization's data base.

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MESOSCALE WAVE ENERGY DISSIPATION OVER HETEROGENEOUS SEDIMENTS

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Measurements describing the evolution of wave energy spectra as waves propagate across a large shoal are described. The shoal is shore oblique, 2 km by 10 km in extent, with relief of up to three meters over bathymetry with ambient depth 10-12 m. The region is sediment starved, and bottom roughness displays spatial variability due to rock outcrops. Field measurements intended to investigate the effects of this shoal on waves, currents, and sediment transport in its lee reveal strong cross-shore gradients in energy density and energy flux, well outside of the surf zone, in conditions of minimal wind, which are attributed to bottom friction. The dissipation displays the expected frequency dependence, in that it decreases in significance as wave frequency increases, but this trend is not as strong as available theoretical predictions would suggest.

1. Introduction

The potential significance of wind wave energy losses induced by bottom friction on the shoreface, outside of the surf zone, has long been recognized (Putnam and Johnson 1949, Bretschneider and Reid 1954). These losses have also been documented in the field (e.g. Herbers et al. 2000, Ardhuin et al. 2004). Neglect of these losses leads to overestimation of nearshore sediment transport rates and over-design of nearshore coastal structures, among other problems.

The magnitude of energy losses due to interactions between surface gravity waves and the seafloor depends on bed characteristics and sediments. Most bedforms are not resolved by numerical models of wave transformation, but may be accounted for by appropriate choice of roughness coefficients in an empirical description of losses due to bottom friction. Even in the absence of significant

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14. ABSTRACT
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